REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE 09/30/2002	3. REPORT TYPE AND DATES COVERED Final, 07/01/00 –09/30/02

4. TITLE AND SUBTITLE
Sensitive quantum-dot infrared photodetector with barrier-limited photoelectron capture

5. FUNDING NUMBERS
DAAD 19-00-1-0426

6. AUTHOR(S)
Professor Vladimir Mitin

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Wayne State University

8. PERFORMING ORGANIZATION REPORT NUMBER
3-31496

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
AMSRL-RO-RI 41327-EL

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

A new design of infrared quantum-dot detector with potential barriers surrounding quantum dots is suggested. The barriers created by optimized interdot doping separate the localized electron ground state and the conducting states. Photocarrier relaxation is drastically suppressed in specially-engineered structures with potential barriers that separate conducting ant localized electron states and prevent electron capture into localized states. Small size and 3D-ristricted geometry of quantum dot result in slow capture of photoelectrons. Suppressed photoelectron relaxation significantly increases the photoconductive gain. The large photoconductive gain results in high responsivity, which in turn will improve NEP and raise the device operating temperature. Results of simulation compared with published results obtained in the group of Professor P. Bhattacharya from University of Michigan, Ann Arbor. Currently they grow and characterize structures with different positioning of doping as it is proposed in our results obtained under this grant.

14. SUBJECT TERMS
Infrared photodetectors, high optical gain, photoelectron capture

15. NUMBER OF PAGES
5

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	**UNCLASSIFIED**	**UNCLASSIFIED**	**UL**

REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

1. List of papers submitted or published under ARO sponsorship during the reporting period.

(b) Papers published in peer-reviewed journals:

1. V. Ryzhii, V. Pipa, I. Khmyrova, V. Mitin, “Dark current in quantum dot infrared photodetectors,” *Jpn. J. Appl. Phys.* **39**, L1283-L1285 (2000).
2. V. Ryzhii, I. Khmyrova, V. Mitin, M. Srocsio, and M. Willander, “On the detectivity of quantum dot photodetector,” *Appl. Phys. Lett* **78**, 3523-3525 (2001).
3. V. Ryzhii, I. Khmyrova, V.Pipa, V. Mitin, and M. Willander, “Device model for quantum dot photodetectors and their dark-current characteristics,” *Semicond. Science and Techn.* **16**, 331-337 (2001).
4. V.V. Mitin, V.I. Pipa, A.V. Sergeev, M. Dutta, and M. Stroscio, “High-gain quantu-dot photodetector,” *Infrared Phys. & Technol.* **42**, 467-472 (2001).

(c) Papers published in conference proceedings

1. V. Ryzhii, I. Khmyrova, V. Mitin, M. Srocsio, and M. Willander, “Physical model and characteristics of quantum-dot infrared photodetector,” Proceed. of 2001 Int. Conf. On Indium Phosphide and Related Materials, 12-18 May 2001, Nara, Japan, pp. 382-385.
2. V. Ryzhii, I. Khmyrova, M. Ryzhii, V. Pipa, V. Mitin, and M. Willander, "Why QDIPs are Still Inferior to QWIPs: Theoretical Analysis," in Photodetectors: Materials and Devices VI, G.J. Brown, M. Razeghi, Editors, 22-24 January 2001, San Lose, CA, Proceedings of SPIE, Vol. 4288, pp. 396-403, 2001.

(d) Papers presented at meetings, but not published in conference proceedings

1. V.V. Mitin, V.I. Pipa, A.V. Sergeev, M. Dutta, and M. Stroscio, “Sensitive quantum-dot infrared detector with barrier-limited photoelectron capture,” International Workshop on Computational Electronics, 22-25 May, 2000, University of Glasgow, Scotland.
2. V.V. Mitin, V.I. Pipa, A.V. Sergeev, M. Dutta, and M. Stroscio, “Quantum-dot infrared photodetector: high sensitivity due to barrier-limited photoelectron capture,” 24th Workshop on Compound Semiconductor Devices and Integrated Circuits, May 29-June 02, 2000, Greece.
3. V. Mitin, V. Pipa, A. Sergeev, M. Dutta, and M. Stroscio, “High-gain quantum-dot infrared photodetector,” QWIP 2000, July 27 – 29, 2000, Dana Point, California.
4. V. Ryzhii, V. Mitin, and M. Stroscio, "Hot Electrons and Negative Differential Photoconductivity in Quantum Dot Infrared Photodetectors," book of abstracts, P2.5, The 12th International Conference on Nonequilibrium Carrier Dynamics in Semiconductors (HCIS-12), Santa Fe, NM, August 27-31, 2001.
5. V. Ryzhii, H. Sagawa, V. Mitin, and M. Stroscio,"Tunneling and Hot Electron Transport in Monopolar Quantum Dot Structures,” 28th International Symposium on Compound Semiconductors ISCS2001, book of abstracts, p. WeP-21, University of Tokyo, Japan, October 1-4, 2001.
6. V. Ryzhii and V. Mitin, “Quantum Dot Infrared Photodetectors: Physical Model and Problems of Computer Simulations”, 8th International Workshop on Computational Electronics, Beckman Institute, University of Illinois, Urbana, October 14-17, 2001.
7. V. Ryzhii, M. Ryzhii, I Khmyrova, R. Suris, V. Mitin, and M. Shur, "Quantum Well and Quantum Dot Infrared Photodetectors: Physics of Operation and Modeling," Proceedings of the XVII International Conference on Photoelectronics and Night Vision Devices, Moscow, Russia, 24 - 29 May 2002.

8. L. Pichl, J. Horacek, V. Mitin, and V. Ryzhii, "Tunneling Effects and Electron Transport in Quantum Dot Structures," 23rd Int. Conf on Low Temperature Physics (LT23), Hiroshima, Japan, August 20-27, 2002.

2. Scientific personal

The following two researches have been supported during 2001 from this grant:

1. Andrei Sergeev, Associate Professor (Research),
2. Victor Pipa, Research Associate,
3. Nizami Vagidov, Ph. D. Student and Posdoctoral Fellow,
4. Dmitri Romanov, Associate Professor (Research)
5. Vladimir Mitin, Professor

4. Scientific progress and accomplishments

Our research on quantum-dot infrared photodetectors has been concentrated on increasing of photoconductive gain and responsivity. Innovative idea in design of sensitive quantum-dot infrared photodetector is to use a structure with quantum dots surrounded by repulsive potential barriers, which are created due to interdot doping. Spatial separation of the localized ground state and continuum conducting states of the electron increases significantly the photoelectron capture time and photoconductive gain. Large value of the gain results in high responsivity, which in turn improves detectivity and raises the device operating temperature.

We have shown that quantum-dot detectors outperform quantum-well structures in photosensitivity because of the geometry of photocarrier dot-traps, restricted in all three dimensions. Photocarrier relaxation may be drastically suppressed in specially-engineered structures with potential barriers that separate conducting ant localized electron states and prevent electron capture into localized states.

The band diagram of the simple quantum dot structure with potential barriers is shown in Fig. 1. The quantum dots are surrounded by repulsive barriers, which are created by interdot doping. Electrons tripped from impurities populate quantum dots and create depletion areas around them. The potential relief in Fig. 1 is produced by electrons bounded in quantum dots and by ionized donors placed outside the dots. Such relief may be obtained by doping of GaAs by Si. If the average number of electrons per dot is large, the positive charge of donors may be considered as is uniformly distributed in a spherical shell. At small number of electrons in the quantum dot, the barrier potential loses its spherical symmetry. In this case the potential distribution is very sensitive to the positions of the charged impurities. Electronic parameters of QD structures may be controlled over a wide range by varying the level of

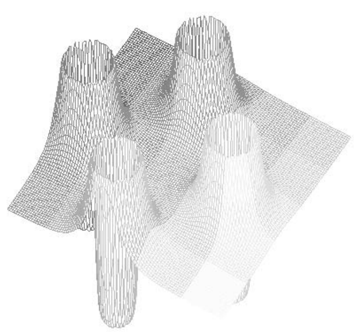

Fig. 1. Band diagram of QD sensor with potential barriers.

intradot doping and changing the characteristic distances associated with the dot structure.

We have shown that electronic parameters of QD structures may be controlled over a wide range by varying the level of interdot doping and changing the characteristic distances associated with the dot structure. We have studied a heterostructure consisting of spherical quantum dots and doped interdot area. Electrons from impurities populate QDs and create depletion areas around dots. The confinement potential *U(r)* is given by the band-offset U_0. The total electron potential energy is the sum of the confinement potential and the electrostatic potential, which is created by electrons bounded in QD and by ionized donors placed outside the dot. Number of confined electrons per dot is determined by the concentration of donors, N_d, through the electroneutrality condition. The suggested structure may be realized in the traditional self-assembled InAs/GaAs QD array. The potential barriers are created by doping of GaAs by Si (it is desirable to avoid intradot doping). Treating N, N_d, and intradot spacing as adjustable parameters, we have found a structure of bound-to-continuum phototransitions.

When IR radiation is incident on the detector, electrons localized in quantum dots absorb IR radiation, exciting them to conductive band. A voltage is applied to the nanostructure through the source and drain contacts. The change of carrier number is detected in the source–drain current. To be captured, the photoelectron should return into the localized QD states. The photelectron can penetrate into the dot due to thermoexcitation over the barrier or due to tunneling through the barrier (see Fig. 2).

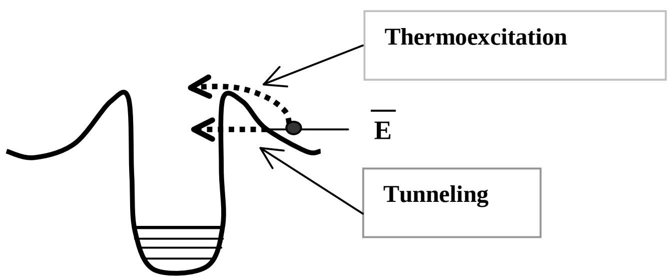

Fig. 2. Processes of photoelectron capture.

With appropriate parameters of the structure, it is possible to block tunneling of photoelectrons into QDs. Potential barriers significantly suppress capture processes and increase the photoelectron lifetime.

At room temperatures, the electron mobility is limited by electron-phonon scattering, while electron relaxation of captured electrons is very fast. Therefore, the photoelectron lifetime is determined by the electron diffusion. Small size and 3D-ristricted geometry of QD results in slow capture of photoelectrons.

We have considered a single QD as the center of the electron capture. We assume that the photoexcited electrons in an interdot region belong to continuous energy spectrum. To be captured, the photoelectron should penetrate into the QD region. The energy relaxation of the electron from the high-energy state to the localized state in QD is realized by electron-phonon scattering. The electron can penetrate into the quantum dot due to thermoexcitation over the barrier or due to tunneling through the barrier. In order to compare rates of these processes, we have investigated the probability of tunneling. We have demonstrated that in the optimized structures thermoexcitation dominates over tunneling for practically all electron states with energies up to V_m (V_m is the barrier height). Thus, the potential barriers very effectively prevent photoelectron capture. With barrier-limited capture the electron lifetime increases by the factor of $exp[V_m/kT]$ in comparison with a flat-band

structure. The photoconductive gain also increases by the same factor. For typical QD structures and the capture time in the flat-band structure of 1-5ps at 200K, we get the photoconductive gain ~100. The high value of the gain allows one to improve detector characteristics.

Thus, QD structures with specially-engineered barriers are very promising sensitive components for IR sensing. Suppressed photoelectron relaxation significantly increases the photoconductive gain. The large photoconductive gain results in high responsivity, which in turn will improve NEP and raise the device operating temperature.

Results were compared with experimental data obtained in the group of Professor P. Bhattacharya and new structures are now grown and characterized in the group to verify the influence of the dopant positioning on infrared detectors performance

Implementation of the proposed research provides valuable experience for our students, and exposes them to modern methods of quantum nanophysics as well as to high-level technique of device modeling. Design, simulation, and optimization issues will be discussed in WSU course ECE 7550, Solid State Electronics, supervised by Professor Mitin.